Experimental and clinical investigations of the possibilities for the reconstruction of flexor tendon injuries

PhD thesis

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1. Introduction, historical background

Restoration of the flexor tendon system after tendon injury within the digital sheath still remains a major problem in hand surgery. Especially difficult the problem if the flexor tendon reconstruction not a primary one. For digits that are classified pre-operatively as being in poor condition, that is, badly scarred, having residual joint stiffness, or with severe bone and soft tissue damage, the outcome after repair is disappointing; this applies as well to reconstruction for salvage of a failed flexor tendon repair. Single stage reconstructive techniques are lacking for the treatment of these injuries, and the most widespread method available and accepted is a staged flexor tendon reconstruction.

In the reconstruction of the flexor tendons we are using tendon grafts in different forms.

The first tendon graft was attempted at the end of the nineteenth century. The exact date is difficult to pinpoint because of the confusion surrounding the term "tendon transplant", which should be used only to describe a tendon graft. In 1882 Heuck a German surgeon repaired an extensor pollicis longus tendon using a tendon graft (29). In 1886 Peyrot reported a case "transplantation in man of the tendon of a dog" to replace the flexor tendon of a middle finger" which has been destroyed"; this resulted in "good healing with partial functional recovery" (63). In 1887 Monod reported a case in which a 5-cm long tendon graft taken from the Achilles tendon of a rabbit was successfully used to repair an extensor

pollicis longus (58). In 1888 Robson took a tendon from an injured digit to fashion an extensor graft on the same hand (68).

At the beginning of the twentieth century being done a lot of work especially in Germany by Lange(43), Kirschner(40), Rehn(67) and Biesalski(1). The later reconsidered the problem of adhesions and the action of tension on sutures, and his work has a profound influence on his contemporaries. In 1912 Lexer from Lena published the results of the first series of ten autograft of flexor tendons (45). Meanwhile the US took over the leading at this period of time in the flexor tendon surgery. In 1911 Lewis and Davis made an experimental study of direct tendon and fascia transplant (44). Mayer published a number of works including three articles on "The physiological method of tendon transplantation."(52-55) In these articles he described the anatomy and physiology of the peritendinous structures and mentioned the necessity for a precise surgical technique, which he called "the physiological method". He also emphasized the importance of ensuring the correct tension of the transfer and the necessity for preserving the gliding planes. He also recommended that the surgeon should personally supervise the postoperative care and resumption of movements. While the clinical applications of Mayer's work were directed more toward the foot and ankle joint, Bunnell in San Francisco turned his interest more toward surgery of the hand. Between the time of his first article on tendon repair in the fingers, published in 1918(11), and his book from 1944(13), he had formulated the principles that now form the basis of tendon surgery.

At that time, primary suturing of flexor tendons was almost always doomed to failure in the digital canal. Although the tendon healing was usually satisfactory, adhesions were so extensive that tendon

mobility was nil. In the face of such consistently poor results following primary suturing in what he called "no man's land" in 1922(12) Bunnell gave his advice: " Close the skin, wait for the wound to heal, then perform a secondary repair as follows: excise the two flexors and graft the profundus tendon alone from the lumbrical to the digital extremity".

This teaching was held as a dogma by generations of surgeons (Boyes, Pulvertaft, Graham, Littler, Tubiana) for the treatment of laesions within "no man's land" (9, 10, 28, 47, 66, 80, and 81).

Tendon grafting is an ingenious attempt at solving some of the biologic problems of tendon repair. Not only can a tendon graft compensate for a loss of a substance, but it also offers the advantage that the sutures are tension-free and can be placed in an optimal position, away from the fibrous pulleys, and the digital sheath.

In practice, most grafts are autogenous. The possibility of using preserved grafting materials has been considered for long time. This would allow the creation of tendon banks and obviate the need for autogenous graft.

For many years, Iselin(38) has advocated the use of acellular grafts preserved in a mercurial solution of Cialit. These grafts are easy to handle and are immunologically more inert then fresh grafts containing living cells. Seiffert and Schmidt(72) have followed the life cycle of these grafts by radioactive labeling techniques and have shown that the collagen is gradually replaced and the allograft is repopulated in 6 or 8 weeks.

In a series of experiments in dogs in which homologous freeze-dried grafts were transplanted into the digital sheats, Potenza showed that the graft is well tolerated and its repopulation by the recipient cell's is not accompanied by adhesion formation in the tendon sheath(65). As

Potenza is pointed out, the term dead graft is too often applied to allografts and heterografts, for although the cells themselves disappear, extracellular collagen remains. An important question is whether this collagen is denaturated in the course of transplantation (25).

Peacock has carried out a series of fascinating experiments on homologous transplantation of the whole flexor tendinous apparatus of the digits with a view to applying his methods to humans (60). His basic premise is that adult tendons and their sheats are devoid of cells capable of synthesizing collagen. If the tendon sheath could be taken intact with it's content. The scarring would proceed between the recipient's bed and outside of the sheats and tendons. Animal experiments confirmed this view and show that immunological reactions are of little significance. This method has been used successfully in humans, even by our group, and by several surgeons (30, 60). Chacha (16) has used composite autogenous grafts taken from the flexor apparatus of the second toe, first in monkey and then in humans. Bíró (2) introduced this method with microsurgical anastomosis of the tendon-tendon sheath unit among patients with poor preoperative prognosis.

Restoring or reconstructing the flexor tendon sheath after tendon repair has been an important step forward. The attitude toward the flexor sheaths has changed considerably over the years. For a long time the tendency was to resects much of the sheaths as possible and to preserve only narrow pulleys. The reasoning was that the sheaths formed a barrier against vascularisation of the graft and there was a risk of the grafts becoming adherent to the fixed structure. Since the studies of Peacock, Potenza, Lundborg, Matthews, Doyle and Blythe. Manske and many others (19, 48, 50, 51, 63, 65) the mechanical and nutritional actions of the

digital flexor sheath are better understood. The most important pulleys must be reconstructed around the graft.

In 1959 Carroll and Bassett (14) used silicone rods to induce pseudosheath formation. Since 1960, Hunter (31) has progressively developed a two-stage procedure using a silicone rod for preliminary preparation of a pseudosheath. The basic concept of this technique is that when a pseudosynovial sheath is formed in response to a biologically inert implant, the cells adapt so that they can effectively accept the tendon graft.

On the other hand the territory of the digital sheath is not really well known. Further investigations are necessary to achieve a better result in the treatment. For this investigations is absolutely mandatory an animal model, on which the new methods, the different surgical procedures are possible to perform. This model should be very similar to the human hand, should be cheep, and the experiments should be reproducible in any place. Previous reports described the chicken foot as a valuable model for flexor tendon research.

Our goal was in the present study, to understand the anatomy and function of the flexor tendon system of the third (long) toe of the chicken feet. We were interested not only for the anatomy of this system, but for the differences between the flexor system of the chicken feet and human hand. We investigated not only the macroscopic differences, but the histological, and ultrastructural findings as well. We do believe these investigations can help to introduce a new model for the bio-pathology of the flexor tendon system. Our findings can help in the introduction of new methods in the flexor tendon reconstruction, especially in the

reconstruction of those fingers that were classified preoperatively as poor.

The next papers are attempts to achieve the aforementioned goals, and the introduction of the results in the clinical practice.

2.

Anatomy of the chicken foot for the experimental investigations in flexor tendon surgery

2.1. Aims

A chicken model for research in flexor tendon surgery is used despite the considerable differences between avian foot and human hand anatomy. In order to properly correlate and interpret the data collected from such experiments, a reexamination of chicken anatomy and terminology was undertaken. Thirty chicken feet were studied anatomically for tendon- tendon sheath structures including vascularisation, flexor systems, and histologic specimens. The data collect show, besides striking similarities between human and avian anatomy, differences critical enough to warrant a reevaluation of previous descriptions of the avian structure.

2.2. Introduction

In the last two decades numerous experimental studies have been undertaken to define tendon physiology and to develop new methods for reconstruction of the flexor tendon system. A better understanding of the physiology of tendon heeling in vivo is still needed. A primary condition of the experimental model is that it must be similar to the human flexor tendon system. Nonhuman primates, while anatomically similar, have the drawback of being expensive to work with.

Based on the work of Lindsay and Thomson (46), a number of researchers have chosen the chicken as an experimental model (3, 17, 20, 24, 37, 61, 62 75, 79). The chicken is a convenient model for experimental tendon studies, since all of the critical structures of the human flexor tendon system are present in the chicken foot. The experimental results are reproducible and the research subjects are inexpensive.

Although chickens have a similar structure to humans in tendon physiology, there are marked differences, e.g., the tendon sheath configuration, the number of tendons, the number and type of the pulleys, the number of phalanges, and the vascular supply. Reports by Farkas et al. (24) have described the anatomy of the chicken toe, but a standard anatomic nomenclature is still lacking (24, 61, 62, and 79).

Our goals in the present study were to review the anatomy of the flexor tendon system of the third (long) toe of the chicken, to expand knowledge of the vascular supply in these systems, and to examine the

structures of the chicken flexor tendon system under light and electron microscopy in comparison with the human system.

2.3. Materials and Methods

Thirty feet from white Leghorn chickens were examined. In five the skin was removed from the plantar surface of the third (long) toe up to the metatarsal level. The tendon sheath was injected with methylene blue and mercurochrom solution at the level of the first IP. Joint. Using a Zeiss stereoscope, all the connective tissues overlying the sheath were removed and the location of the tendon sheath, as well as the number and position of the pulleys were examined. In five feet the tendon sheath was incised longitudinally over its full length and tendon locations, tendon insertions, and vincula were examined.

In five feet, the tendon-tendon sheet unit of the third (long) toe was removed and fixed in 10% formalin. The blocks were embedded in celloidin-paraffin, and serial sections were made. The slides were stained with HE, PAS-HE, Van-Gieson and Krutsay stain.

For scanning electron microscopy, blocks were made from the membranaceous part of the sheath at the level of the second phalanx, from the C3 pulley, and from the visceral tenosynovium at the same level in five digit samples. The blocks were fixed in 2,5% buffered glutaraldehyde and dehydrated. Then the specimens were dried with a critical-point drying method, coated with gold, and examined in an EM ASID 4 and a TESLA BS 300 electron microscope.

2.4 Results

2.4.1. The tendon sheath

The chicken's third (long) toe flexor tendons are covered by a tendon sheath extending from the insertion of the flexor profundus tendon just below the trifurcation of this tendon at the level of the distal tarso-metatarsus. It is an important difference between the chicken foot and the human flexor system that the tendon sheath of the third (long) toe of the chicken is divided into two parts by a thin membrane at the level of the vinculum longum insertion. (Fig.1)

Fig 1. The structure of the tendon sheath. The proximal part is filled with methylene blue, the distal part with mercurochrom solution. The divided sheath is clearly visible.

The distal part of the tendon sheath forms a „cul de sac" at this level. The sheath - a thin, fragile, connective-tissue membrane - has thickenings called pulleys, similar to the structures present in the human hand. Recently Telepun et al. (79) published a new description of the pulley system of the chicken's third (long) toe. We found that this toe of the chicken has five pulleys; namely one at the level of the metatarsophalangeal joint, one at the distal part of the distal part of the first, second, and third phalanges, and one above the third I.P. joint. (Fig. 2A, B, C, D.)

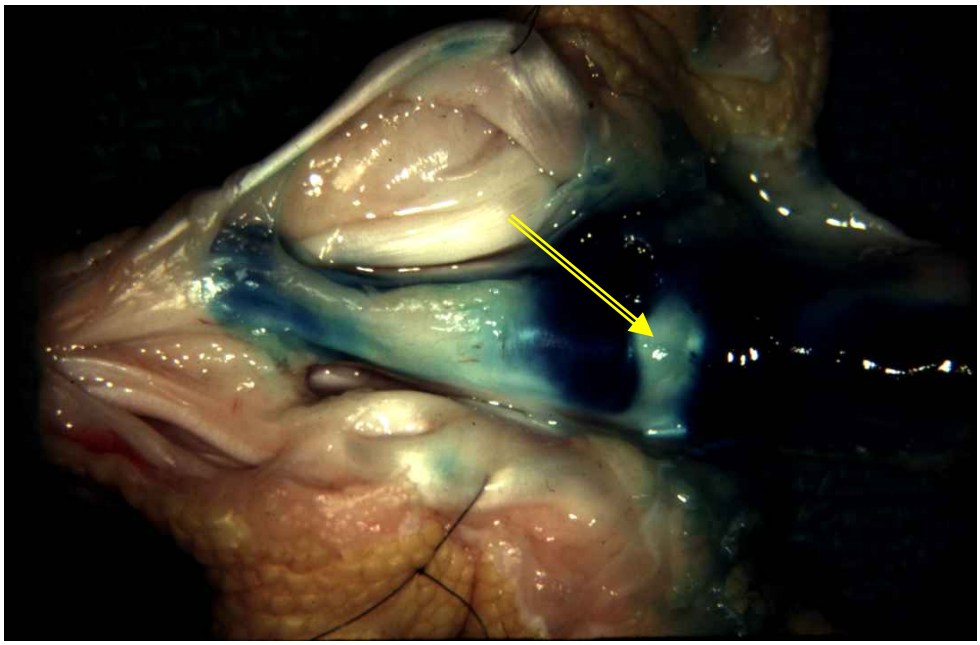


Fig. 2.A. The first pulley of the chicken third (long) toe. (Yellow arrow.) Note the „cul de sac" (red arrow) , where the proximal part of the tendon sheath begins.

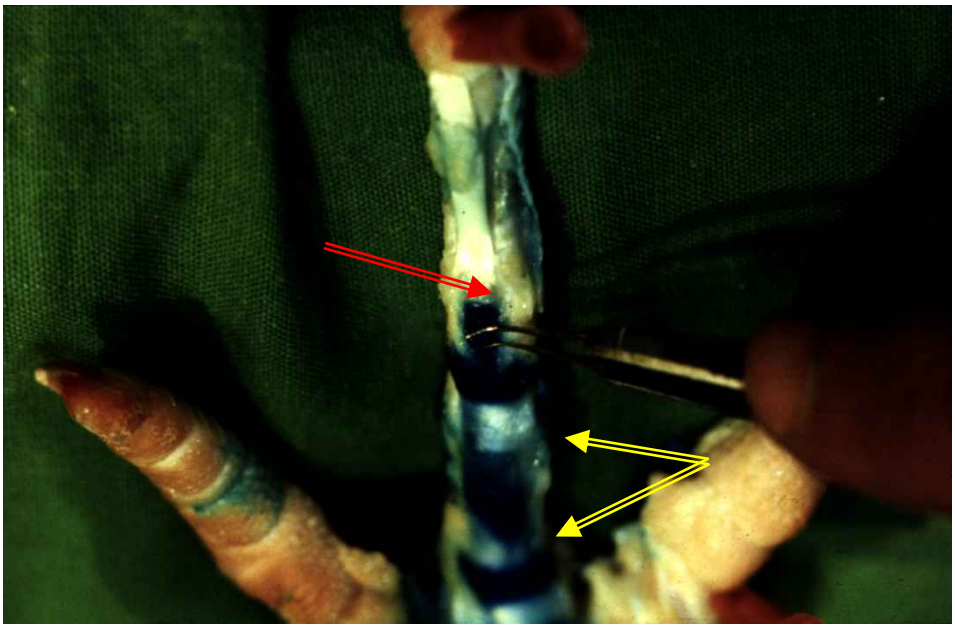


Fig.2.B. The second and third pulley (yellow arrows). Note the extension of the proximal part of the tendon sheath (red arrow).

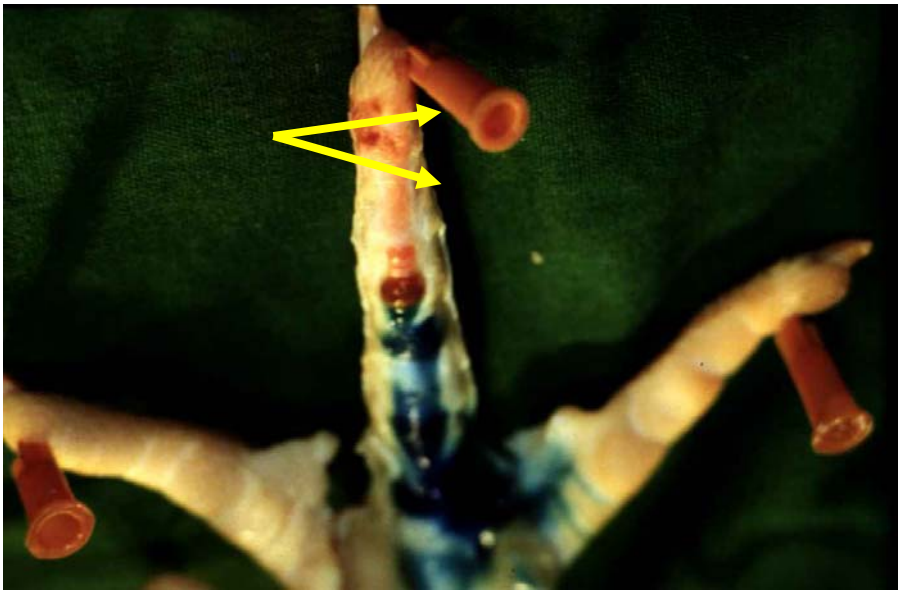


Fig.2.c. The fourth and fifth pulleys of the chicken third (long) toe (arrows).

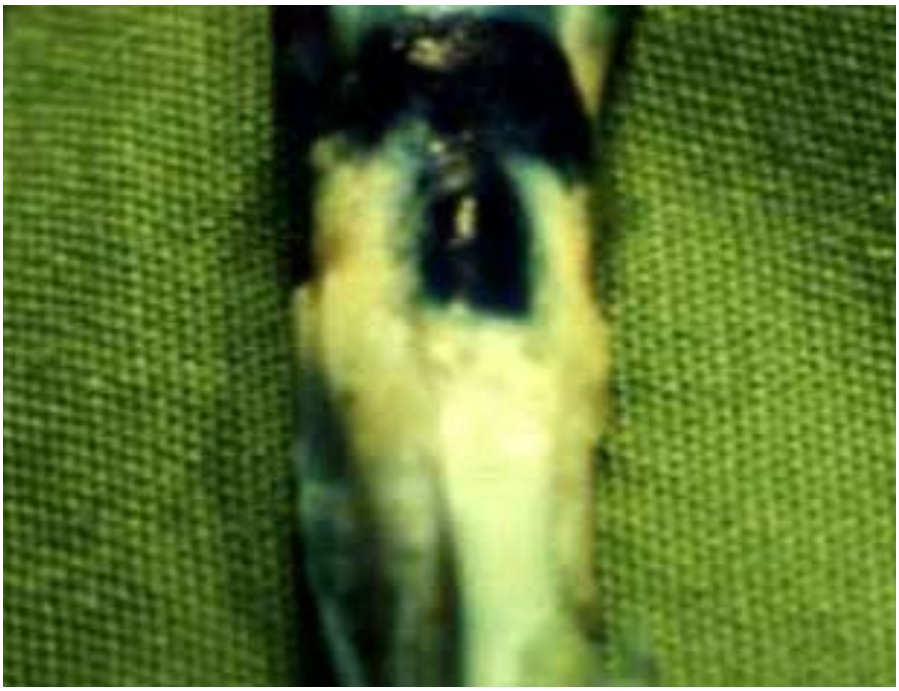


Fig.2.D. The border between the two parts of the tendon sheath.

We propose to classify these structures as C1-5 from proximal to distal. Pulleys C1 and C4 are wide, about 5-7 mm in size and weaker then pulleys C2 and C3. Former contain fibers, both circular and cruciform orientations whereas pulleys C2 and C3 are narrow structures, 2 mm in size contain circular fibers. Pulley C5 is thin fragile structure containing circular fibers.

2.4.2. The flexor system

The flexor system of the chicken's third (long) toe is composed of three tendons (24, 42), namely, the musculus flexor peforatus, the musculus flexor perforans and perforatus, and the musculus flexor profundus. This is a further considerable difference between the human and chicken flexor systems (24). The musculus flexor perforatus (FP) is a wide, thin tendon that bifurcates in the middle portion of the first phalanx, inserting into the distal lateral part of this phalanx. The musculus flexor perforans and perforatus (FPP) is a wide flat tendon that bifurcates at the middle portion of the second phalanx, and each slip inserts at the lateral surface at the base of this phalanx. The musculus flexor profundus (FDP) passes through the bifurcation. The first two of the three tendons in the flexor system are single structures from origin to insertion (24, 61).

The musculus flexor digitorum communis has a common trunk at the tarsometatarsal level and trifurcates just above the level of the metatarsophalangeal joint and, inserting at the base of the fourth phalanx

and passing through the bifurcations of both the perforatus and superficialis tendons.

The tendons FP and FPP are single structures from origin to insertion, while the flexor profundus is a branch of the flexor digitorum longus.

2.4.3.Vincula

Our observations showed tissue connections, called vincula, between the tendons and the tenosynovial membrane in the chicken digit. They are mobile structures covered by an areolar layer of mesotenon. Microscopically, they have been described as being more cellular then the tendon and contain a large amount of elastic tissue possessing a central arteriole straddled by two venules (46). There are two short vincula to the profundus tendon originating from the third IP volar plate. Tendon FPP also has a vinculum not previously described. It originates from the second IP volar plate. The FP has no vinculum.

2.4.4.Vascular and nerve supply

The main vessel of the chicken foot is the arteria dorsalis pedis originating from the arteria tibialis anterior. It divides into two branches at the midportion of the tarsometatarsus. These branches, coursing beneath the tendon of the common extensor, are the main arterial supply

for the four digits. This vessel in the third (long) toe courses on the dorsolateral aspect of the digit, close to the flexor tendon sheath (Fig.3).

Fig.3. The vascular supply of the chicken leg.

Fig 4. The circulation of the chicken feet. Note the vascular supply is more similar to the human feet then the human hand.

The arteria plantaris medialis, which is the terminal branch of the arteria tibialis medialis, is located on the plantar surface of the tarsometatarsus, covered by flexor tendons. This artery is approximately one-third smaller then the arteria dorsalis pedis(Fig4). The arteria plantaris medialis divides into branches for the digits in the sole and serves as the arterial supply for the medial portion of each digit, running along the dorsomedial portion of the tendon sheath.

The arterial supply of the proximal portion of the flexor tendons in the third toe comes from the arteria plantaris medialis. One branch reaches the tendons at the mid-tarsometatarsal level; other branches enter into the tendons at the proximal „cul-de-sac" of the tendon sheath.

The distal portion of the flexor tendons is supplied by branches entering the tendons through the vincula and their insertions. At the level of each vinculum, there are connections between the medial and lateral digital arteries, forming digitoplantar arches (Fig.5). Like in the human structure, the vincular arteries originate from these arches (76, 82).

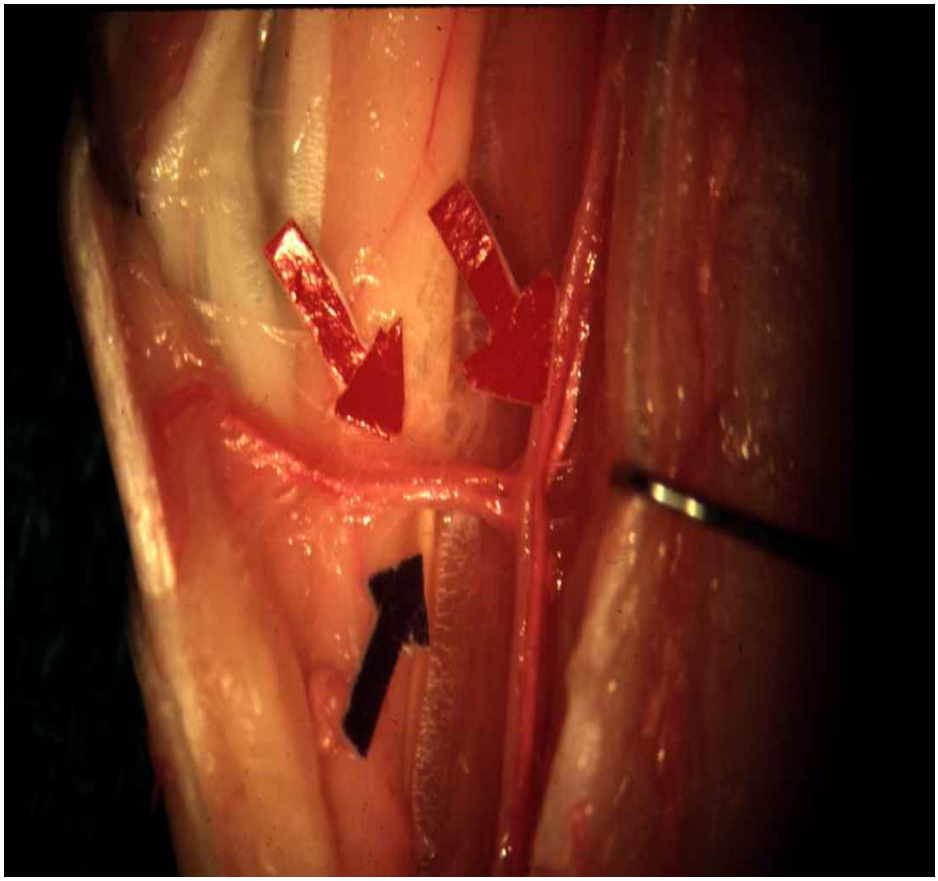


Fig 5. The vincular circulation of the long (third) toe of the chicken feet.

There is a large vein at the dorsomedial aspect of the third (long) toe and a smaller vein joined the medial neurovascular bundle.

The nerve supply for the third (long) toe is provided by the nervus digitalis tertius medialis, originating from the nervus fibularis profundus, and by the nervus digitalis tertius lateralis, a nerve originating from the nervus fibularis superficialis (42).

2.4.5. Light- and scanning electron-microscopic studies

Sections made from the tendon-tendon sheath unit at the portion between the third and fourth pulleys reveal the visceral and parietal parts of the tenosynovium. The parietal part has an external well-developed layer, rich in collagen fibers (Fig. 6A, B).

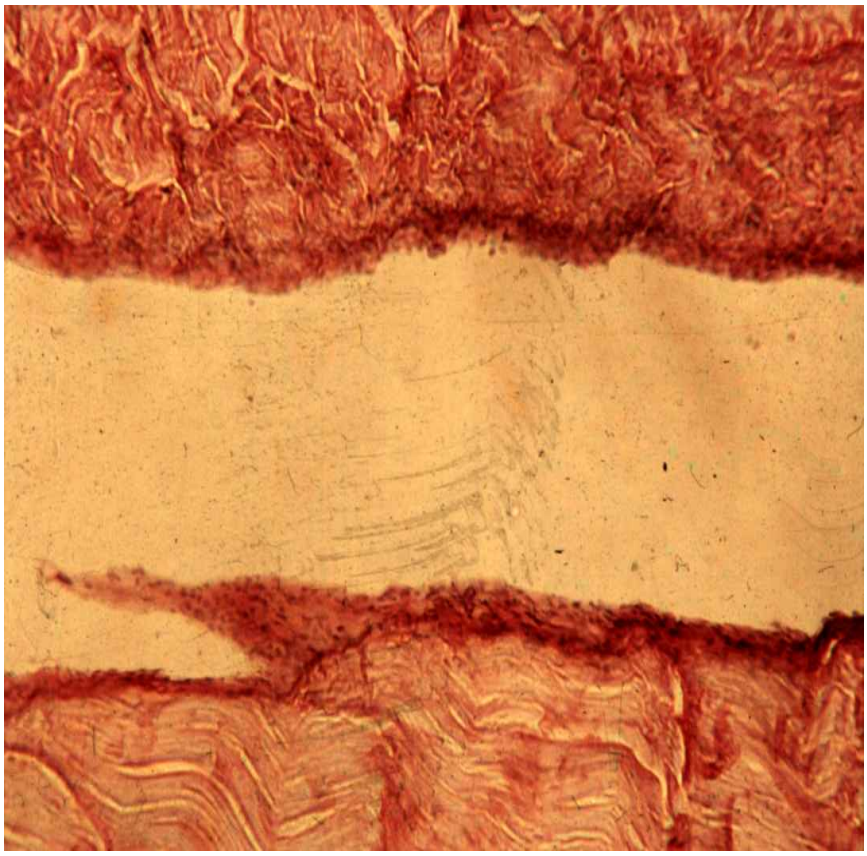


Fig 6.A. The parietal and visceral surface of the normal chicken tenosynovium HE.

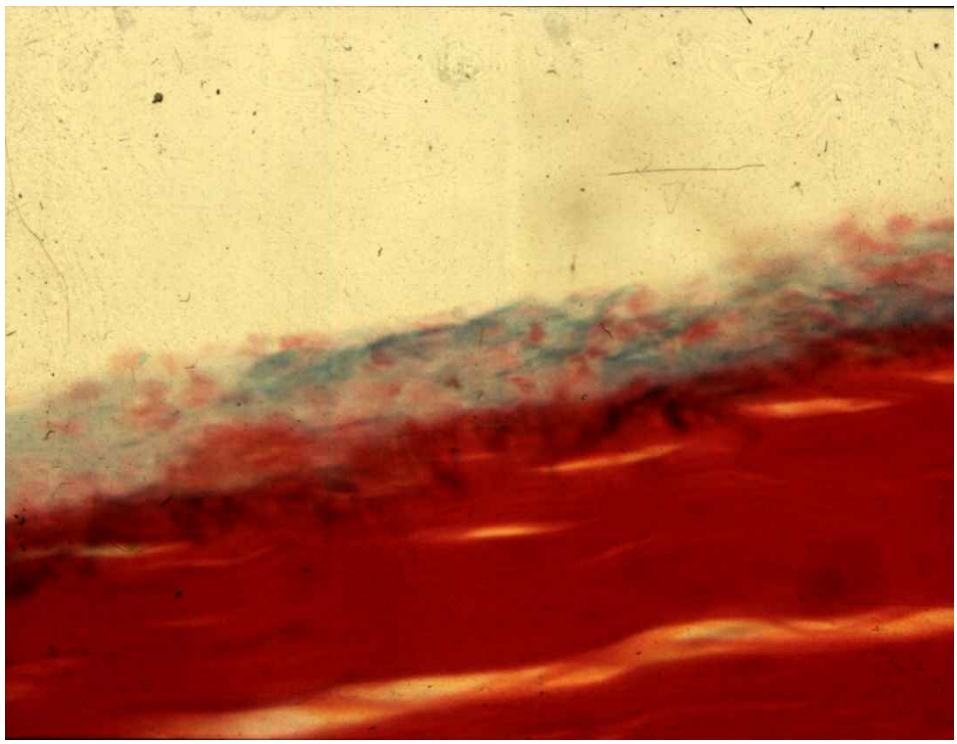


Fig.6.B. The visceral layer of the normal chicken tenosynovium. Krutsay trichrome.

These fibers course in several directions and between them fibroblast can be seen. As is evident in higher magnification, the synovial cells form one layer or two. Each of these cells has an oval nucleus with a loose chromatin structure. The flexor tendon, covered by a thin synovial layer (the epitenon), lies on the other side of the synovial space. The tendon has a typical, compact, collagen-fiber structure with tenocytes. There are a smaller number of synovial cells on the surface, and the nuclei of these cells are more elongated and flatter, those in the parietal layer.

Scanning electron micrographs of the chicken's parietal tenosynovium show an undulating wrinkled surface, especially at higher

magnification the synovial cells may swell out from the surface and interconnected with fibrils and filopodia.

The surface of the visceral tenosynovium has longer, flatter wrinkles and also reveals vesicula and granula (Fig 7).

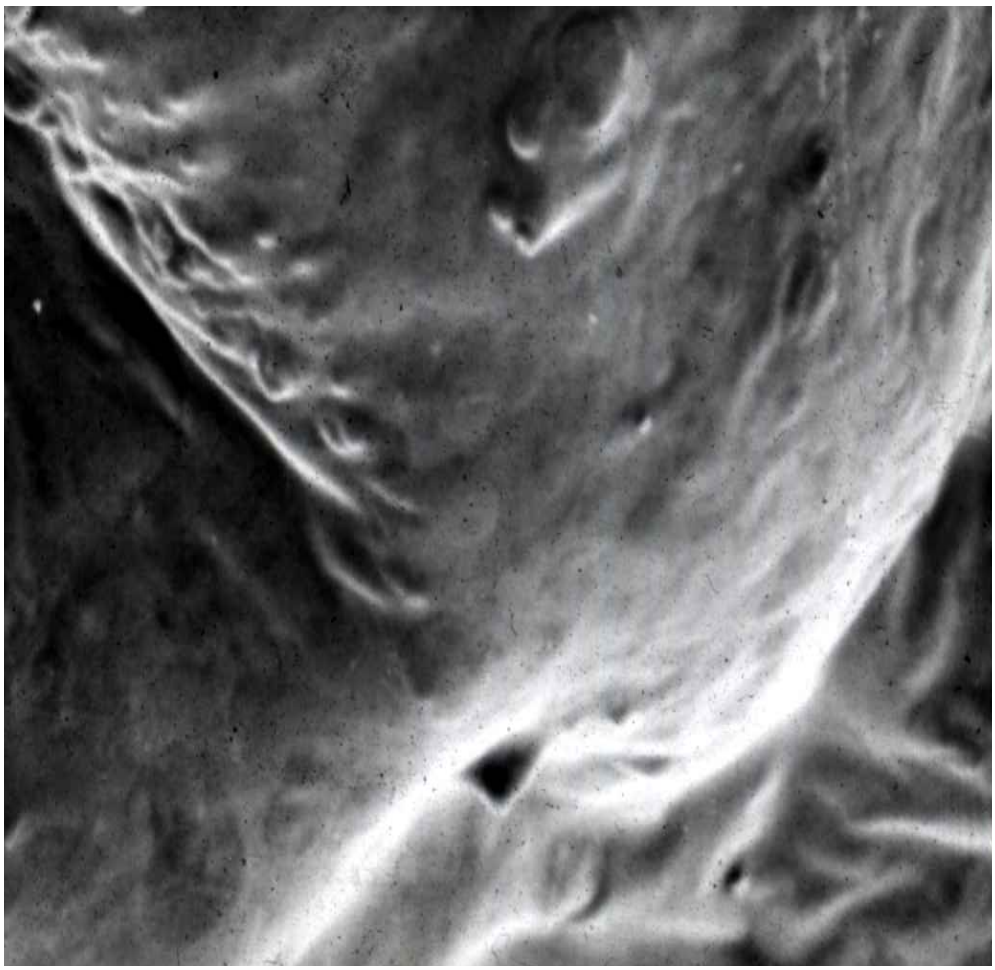


Fig.7. Surface of the visceral tenosynovium.

2.5. Discussion

The anatomic findings described concur generally with the descriptions published by Farkas et al.(24) and Koch (42), however, more detailed and additional observations were made in our dissections.

The first of these differences is in the composition and classification of the tendon sheath. In contrast to Farkas et al. (24) , the dorsal portion of the tendon sheath cannot be separated from the underlying periosteum and volar plates; it can be removed only together with associated structures. The sheath is firmly attached to the bifurcation of the flexor perforatus and superficialis tendon as well. The main difference is that the tendon sheath of the chicken's third (long) toe is divided into two parts by a thin membrane. The FDP is running in a separate sheath from the vinculum longum insertion. The importance of this finding is that the flexor tendon experiments are usually done in this region.

Regarding the pulley system, Farkas et al. (24), and similarly Telepun et al. (79) described only two short pulleys on each of the phalangeas 1 and 2. We found the existence of five annular pulleys. Because of these new findings, we propose to classify these structures as C 1-5 from proximal to distal.

The construction of the chicken C1 and especially C4 pulleys shows a striking similarity to the human AP1 pulley in the tendon-tendon sheath anatomy. In addition no pure cruciform ligaments exist,

although cruciform fibers can be observed. From a functional aspect, chickens exhibit three pulleys, C2, C3 and C4, while in humans the number of pulleys is two, an AP1 and an AD1 pulley (76). The difference in the number of pulleys can be correlated with the extra phalanx in the chicken digit.

The five annular pulleys described above differ markedly from those reported by Strauch and de Moura (76) and by Doyle and Blythe (18) for human hand anatomy. In this respect the most significant difference between the two species is that chickens have three flexor tendons versus the two in humans.

Renaming of the flexor tendons may result in a more concise and compatible comparison to human hand anatomy.

We suggest the following nomenclature for tendons:

New	**Previous**
Flexor digiti superficialis vs. Proximalis - FDSP	Flexor digiti perforatus - FDP
Flexor digiti superficialis vs Distalis - FDSD	Flexor digiti perforans perforatus - FDPP
Flexor digiti profundus - FDP	No change

The FDSP has already been described (17) as corresponding to the intrinsic muscles of the human hand.

The vascular supply of the chicken foot corresponds more similarly to that of the human foot, rather than to that of the human hand. Our findings describe more clearly then the previous ones the two vessels from the arteria medialis, witch arterialize the digits and sole of the chicken foot. In conducting experimental surgery, therefore, the researcher must be careful not to injure the vessels to the toes. Our findings also reveal the existence of a vinculum originating from the second IP volar plate to the FDPP tendon. Our light- and electron-microscopic studies confirm the data reported by Inoue at al. (37) and established the similarity of the histological structure of the tendon-tendon sheath unit between the human hand and the chicken foot. Since the chicken foot is a weight bearing structure and is designed to grasp and/or hold (in a modified primate fashion) and therefore a parallel between the human hand and the anatomic function of the chicken foot cannot be drawn.

2.6. Summary

The intention of this study was to provide additional information for designing and evaluating experiments for researchers who use chickens as experimental model for flexor tendon surgery.

While the similarities between the flexor tendon systems in the human hand and the chicken foot remain significant, there are considerable inherent differences. Nevertheless, the chicken is an excellent in vivo model for flexor tendon research. The description of the

intact mechanism of the tendon-tendon sheath unit, its vascular supply, and its corresponding histology, should aid researchers in their observations of changes and developments in the mechanism during experimental procedures.

3.

Histology and Ultra structure of the Normal Tenosynovium and Pseudo sheath in Chickens and Humans

3.Aims

The histology and ultrastructure of the intact flexor tendon sheath and the pseudo sheath of the chicken foot and the human hand were studied. A regular parietal and visceral layer was found both in the normal sheath and in the pseudosynovium using light microscopy and scanning electron microscopy. The surface of the normal synovium shows folds and cellular protrusions covered with fibrils and vesicles. The architecture of the pseudoynovial surface is similar after silicone rubber implant. Two types of synovial lining cells were observed using transmission electron microscopy. The ultra structural features and the possible function of these cells are discussed. Type A cells have phagocytic characteristic, type B cells possess secretory capacity. These findings were similar concerning the normal tendon sheath and pseudosynovium both in chickens and humans. Hypothetically, the

described regular structure of the newly formed tenosynovium should guarantee the nutritional supply and the gliding of the transplanted tendon under ideal conditions. The elaborate healing process and the influencing factors of the tendon healing emphasized.

3.2 Introduction

The healing of the injured, especially the severely injured, flexor tendon in zone 2 is a very complicated process depending on biologic, functional, and clinical factors. Hunter (32) has described a two-stage procedure for the reconstruction of scarred tendon in this zone using a silicon rubber implant to develop a new tendon sheath. This method has been proposed by other authors as well. During the last twenty years a lot of experimental and clinical data were published, but nowadays different opinions exist in the judgment of the repair process. The origin of the in growing cells, the nutrition of the tendon graft, and the capacity of the new collagen synthesis are uncertain.

In recent work the following questions were investigated using light microscopic, scanning electron microscopic, and transmission electron microscopic investigations:

1. What is the structure of the parietal and visceral layers of the normal tenosynovium and the pseudo sheath?
2. Where are the synovial cells and what is the morphology and function of these cells?
3. What is the mechanism of tendon healing within the pseudo sheath?

3.3Material and methods

Young adult chickens were used as experimental animals because of the anatomic similarity between their digits and those of humans. Fresh human cadaver digits, amputated fingers, and little pieces of the tendon sheath of injured patients were studied. A total of 45 chickens and 18 human materials were used. Ten chickens and 6 humans served as controls. All the animals that suffered postoperative infection or an operative failure were excluded from the recent study. The experimental model was similar to human flexor tendon injuries, including scar formation and the two-stage reconstruction.

All chickens were anaesthetized with ketamine and local nerve block was given to the digital nerves using 1% Lidocaine. First the flexor digitorum profundus (FDP) tendon of the long toe of the chicken foot was injured at the level of the insertion of the flexor digitorum superficialis (FDS). After 4 weeks the long toe was explored using a zigzag incision, and the scarred tissues were removed together with the remaining FDP stumps from the territory of the tendon sheath. A silicone rubber rod was implanted into the digit for replacement of the missing FDP tendon. A plaster cast was applied for two weeks. Six weeks after the silicon rubber

implantation, the silicone rubber implant was replaced with a tendon graft taken from the other foot using only a small proximal and distal incision. A plaster cast fixation was applied immobilizing the metatarsophalangeal (MTP) and interphalangeal (IP) joints in flexed position for two weeks. Normal activity was allowed for the animals after the cast was removed. Specimens were obtained from the normal tendon sheath and from the pseudo sheath 6 weeks after the silicone implantation and 4 weeks after replacing the silicone implant by autogenous tendon graft. For light microscopy, paraffin sections were stained with haematoxylin-eosin and with Krutsay trichrome.

For scanning electron microscopy, samples were fixed in 2.5% glutaraldehyde at pH 7.4, were dehydrated in grading alcohol, and dried in a critical point dryer apparatus. The specimens were coated with gold and examined in a TESLA BS 300 scanning electron microscope. For transmission electron microscopy, tissue was fixed in 4% glutaraldehyde and 2% osmium tetroxide, embedded in Durcupan ACM and examined with a JEM 100 B type electron microscope.

3.4 Results

3.4.1.Group I: Light microscopic and ultra structural morphology of normal chicken and human tendon-sheath unit.

3.4.1.1.Light microscopy:

In the longitudinal section of the normal chicken tendon, tendon sheath unit, the synovial cells of the visceral part form one layer and the lining cells of the parietal sheath are generally in two layers. The cells have ovoid nuclei. The parietal membrane shows rich vascularization in loose connective tissue. The outer layer of the tendon sheath consists of dense collagen bundles. (Fig.8) The histology of the human flexor tendon-tendon sheath unit is similar to the structure described previously. (Fig9)

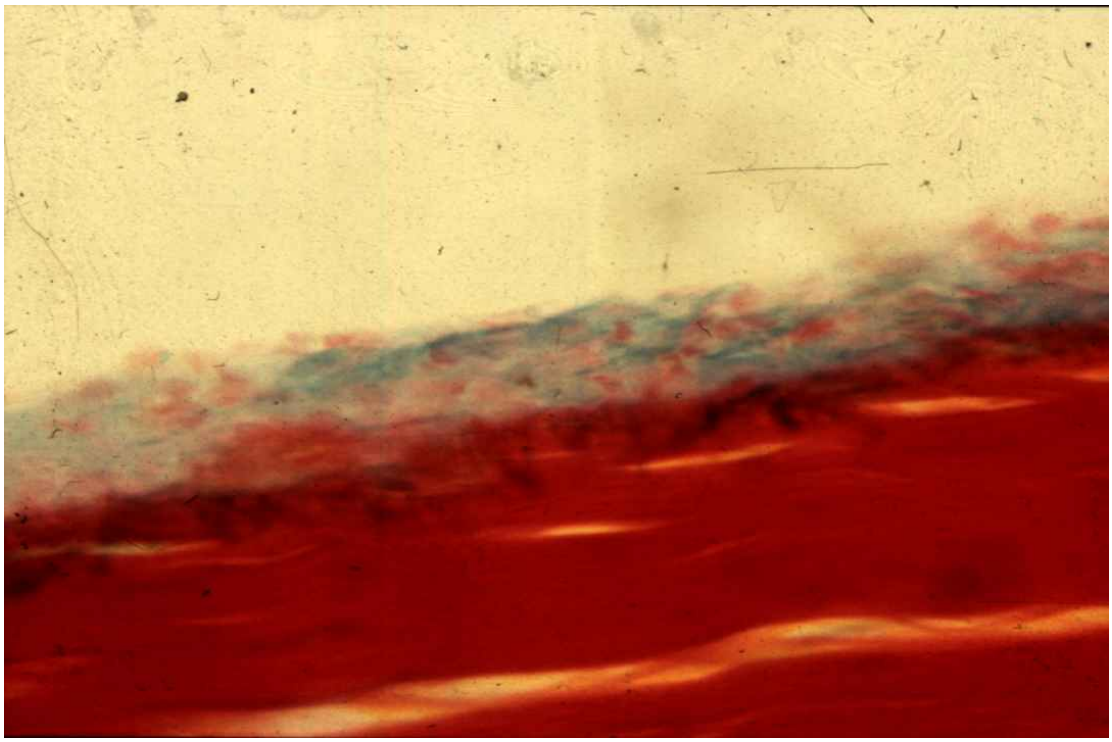


Fig 8. Chicken tenosynovium at higher magnification. HE (x160)

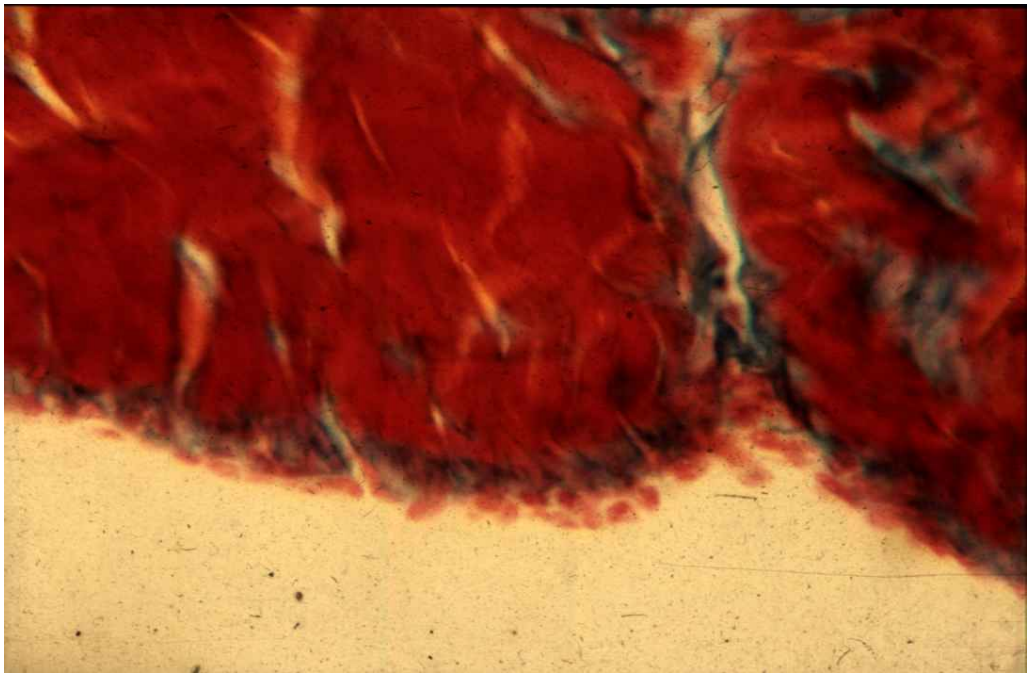


Fig.9. Human parietal tendon sheath.

3.4.1.2. Scanning electron microscopy.

The architecture of the surface of the chicken visceral tenosynovium shows slight, parallel folds. (Fig10)

Fig.10. Surface architecture of the parietal layer showing folds, fine fibrillar network (x300).

The surface is covered with fibrils and vesicular particles (Fig11.).

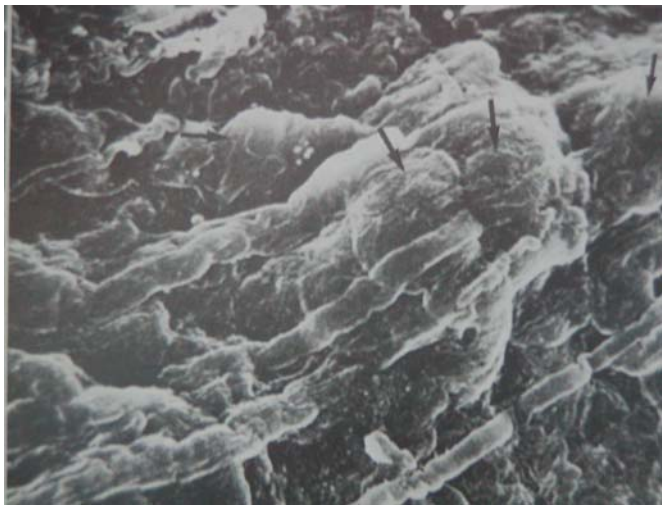


Fig11. Protrusions of synovial cells *(arrows)* covered with fibrils. Parietal tenosynovium (x1000).

Two types of synovial cells are observable in the chicken and human tenosynovium(Fig12).

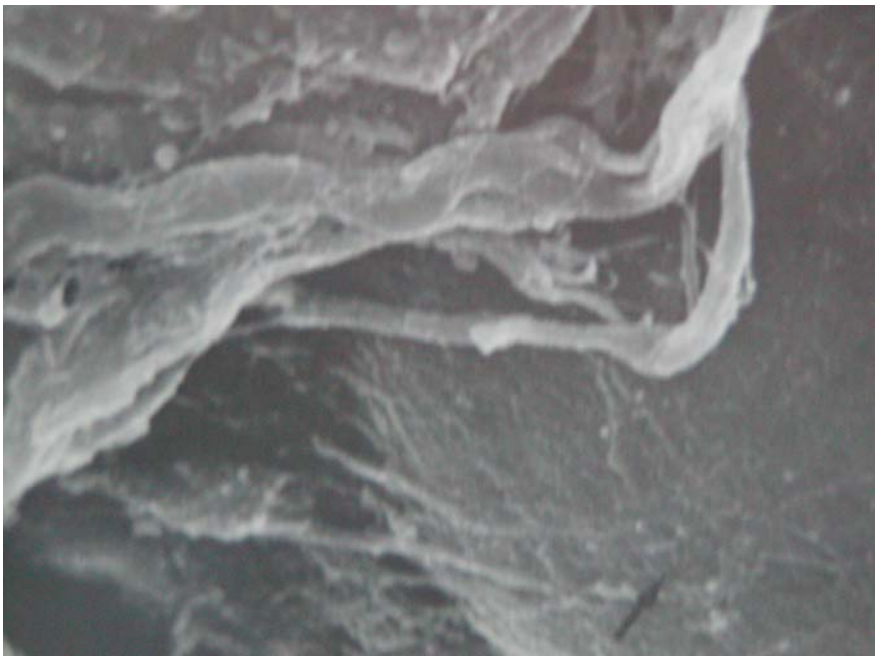


Fig. 12.Chicken parietal synovium. Synovial cell at high magnification *(arrow).* Fibrils and vesicular particles attached to

the cellular surface. *(x6000).*

3.4.1.3.Transmission electron microscopy:

The type A cells are present at different levels of the synovium. Theses phagocytic cells have many vacuoles, vesicles, lysosomes, filopodia, a prominent Golgi complex, but only little endoplasmic reticulum is visible. Fig.13, 14.

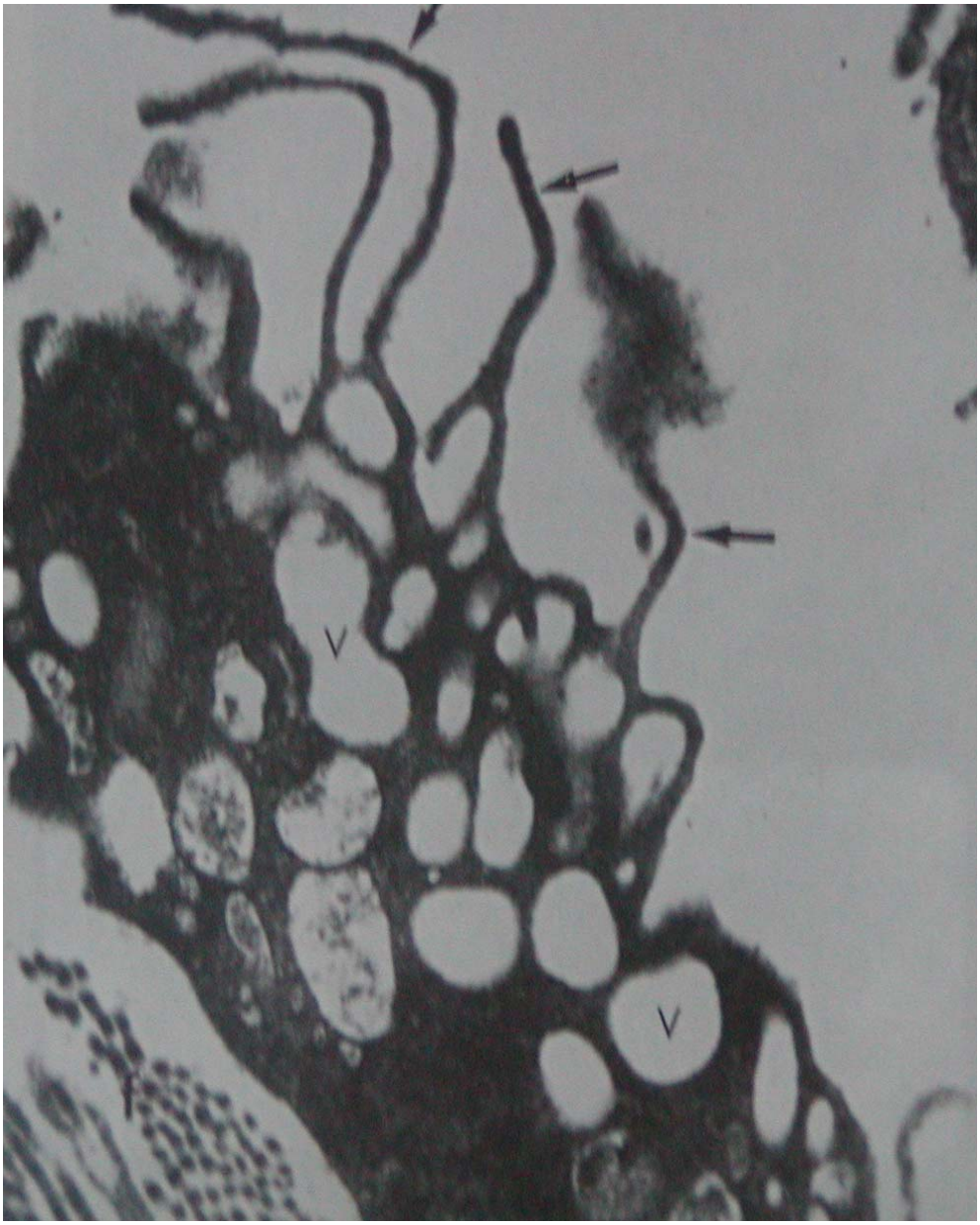


Fig.13 Normal chicken tenosynovium. Cytoplasmic part of a type A cell with many filopodia *(arrows)*, vacuoles *(v)*, collagen fibrils *(f) (x8000)*.

Fig.14 Normal human tenosynovium. Type A lining cell shows scanty endoplasmic reticulum, vacuoles *(v),* filopodia *(arrows),* nucleus (N) *(x5000).*

The type B cells have distinct endoplasmic reticulum, wide cisternae, namely, the ultrastructural features of a secretory cell. Fig.15. There is intermediary cells between types A and B as well.

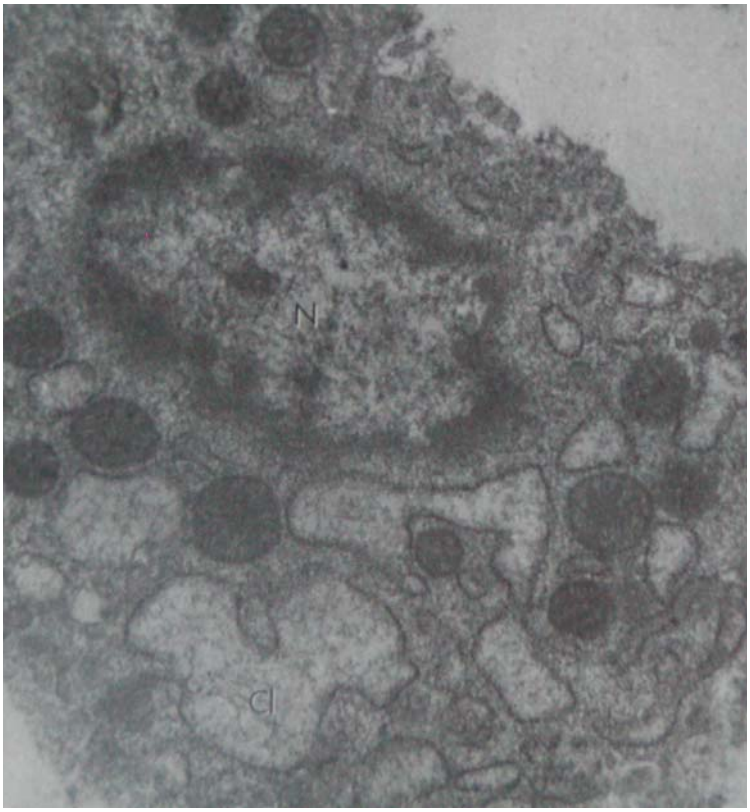


Fig.15 Type B cell with profuse rough endoplasmic reticulum: wide cisternae *(CI),* mitochondria *(M)* in the chicken parietal synovium, nucleus *(N) (x13,000).*

3.4.2.Group II.: The structure of the newly formed synovium (pseudosheath) 6 weeks after silastic rod implantation.

3.4.2.1.Light microscopy.

The newly formed sheath appeared thicker than normal and varying in different places. The synovial cells of the chicken parietal sheath were arranged in two or three different layers in the longitudinal sections supported by vascular connective tissue. Fig.16

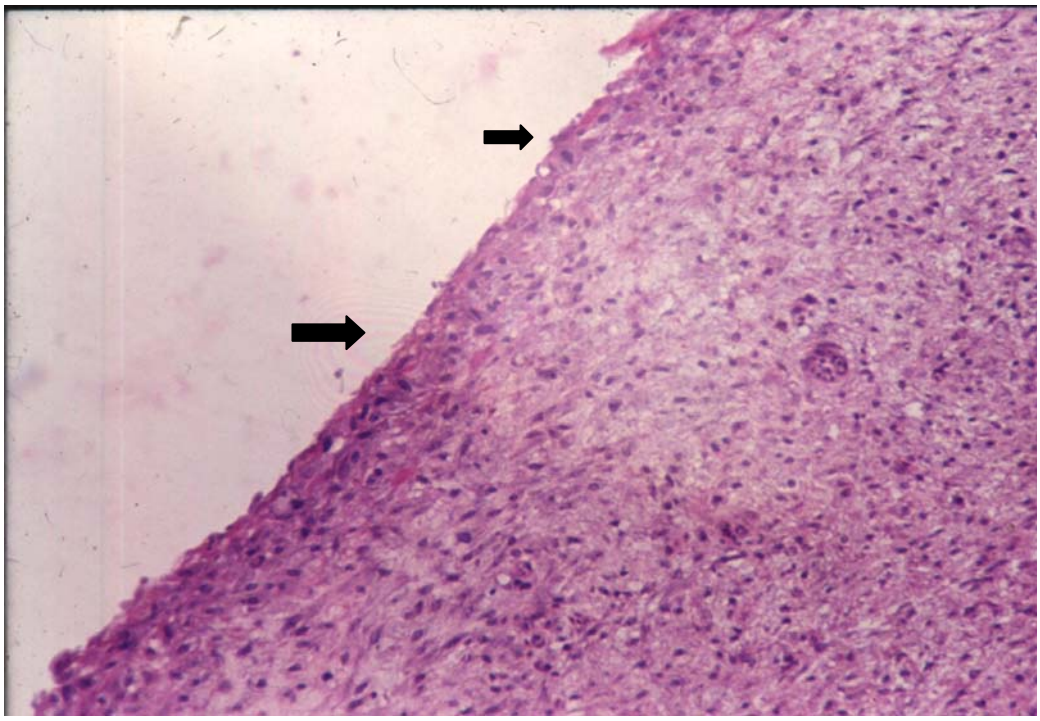


Fig.16 Longitudinal section of chicken pseudo sheath. Lining cells (arrows) and underlying connective tissue. Haematoxylin-eosin stain (x160)

3.4.2.2.Scanning electron microscopy:

The surface of the parietal tenosynovium is similar to the normal chicken tenosynovium. Uneven surface is visible. The fold and lining cells are generally in longitudinal direction. Fig.17,18.

Fig.17 Chicken pseudosynovium. SEM demonstrates the surface Structure of the pseudosheath after removal of the silicone rubber implant *(x300)*.

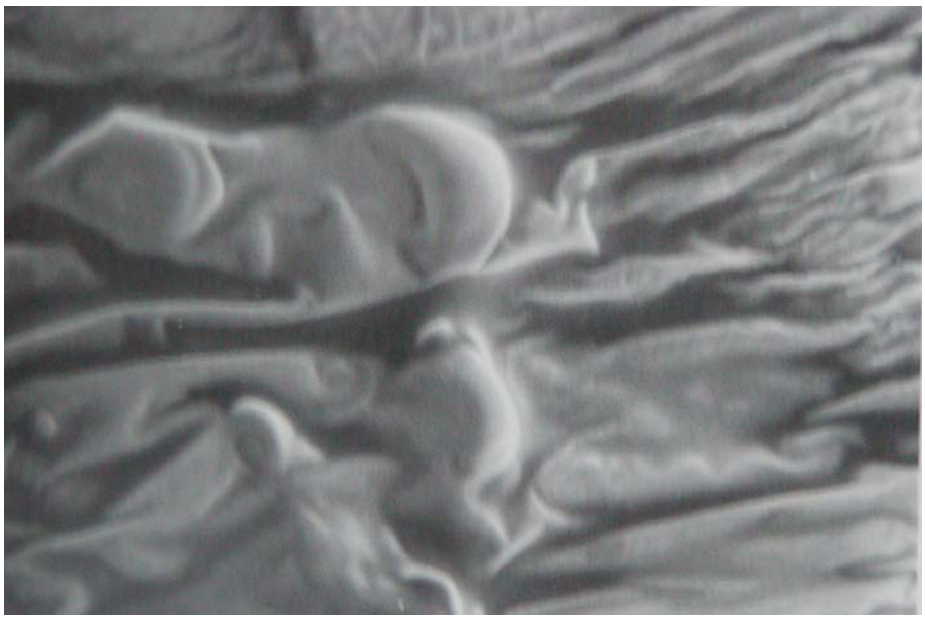


Fig18. Surface folds and lining cell protrusions at higher Magnification *(x1000)*.

3.4.2.3.Transmission electronmicroscopy:

Human pseudosheath was investigated, finding a similar ultrastructure to the normal chicken and human tenosynovium. Ultrastructure of type A cells posesses characteristics of phagocytic capacity (vacuoles, filopodia, lysosomes, little endoplasmic reticulum). Fig.19,20.

Fig.19 Type A synovial cell in human pseudosheath showing nucleus *(N),* vacuoles *(V),* filopodia *(arrows)*; lttle rough endoplasmic reticulum *(x8000)*.

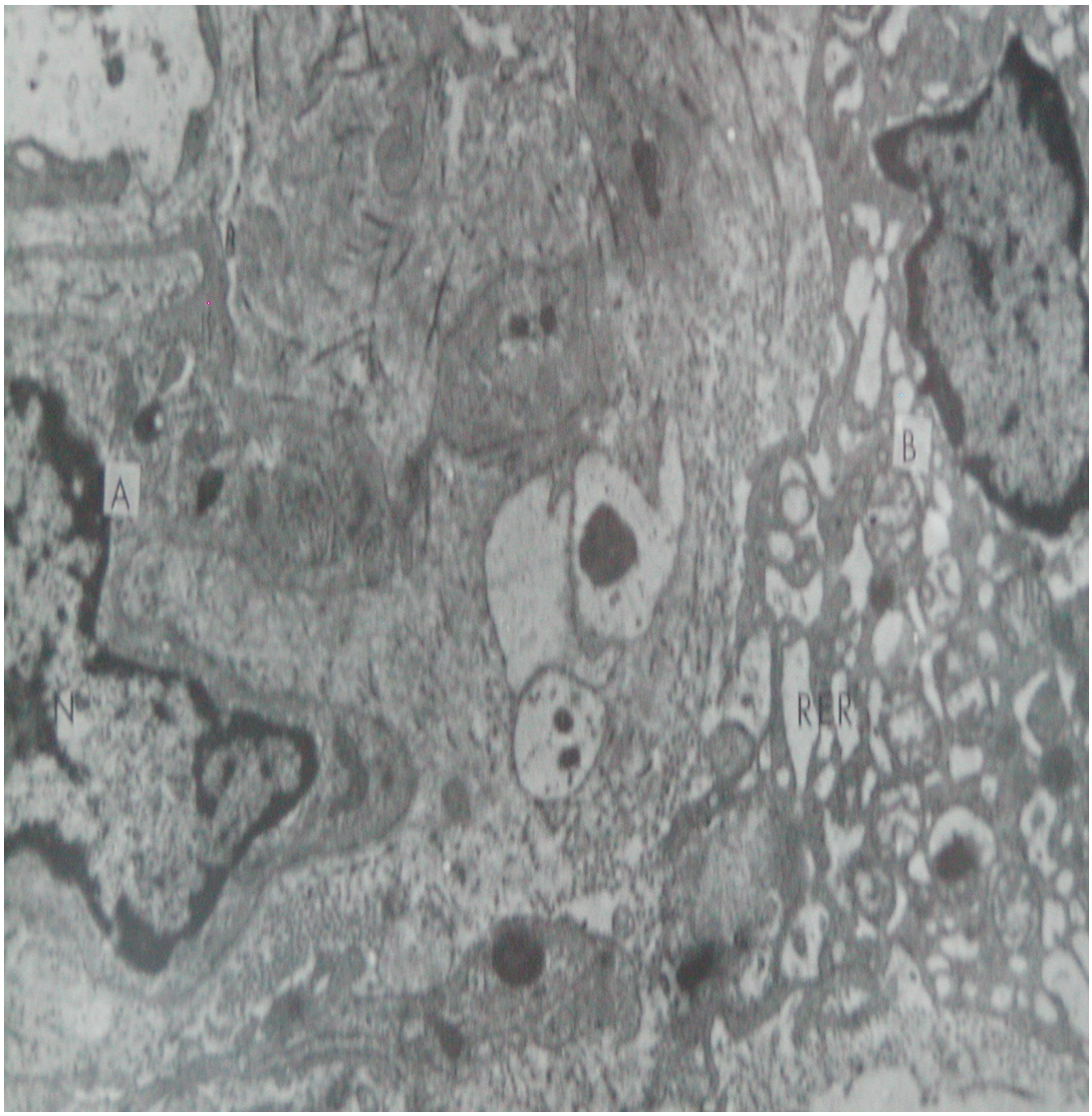


Fig.20 Human tenosynovium. Type A cell *(A)* characterised by little endoplasmic reticulum. Type B cell *(B)* shows an abundant endoplasmic reticulum *(RER)* nucleus *(N) (x6000)*.

The type B cells have ultrasctructural features of a secretory cell showing extensively developed endoplasmic reticulum, wide cisternae, prominent Golgi complex. Fig.20,21.

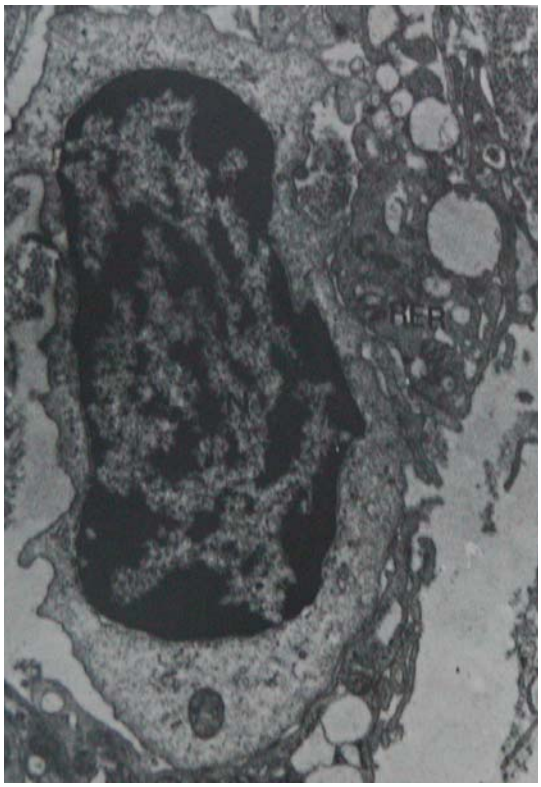


Fig.21 Type B cell in the human pseudosnovium nucleus *(N).* Well developed rough endoplasmic reticulum *(RER),* wide cisternae and mitochondria are visible. *(x12000)*

3.4.3.Group III.:

The structure of the pseudo sheath 6 weeks after replacing the silicone rubber implant by autologous tendon graft

3.4.3.1.Light microscopy:

The histology of the newly formed parietal and visceral sheath is similar to that of the normal flexor tendon sheath. The synovial cells of the

parietal synovium are in two or three layers, and the surrounding tissue contains more bundles. Fig.22.

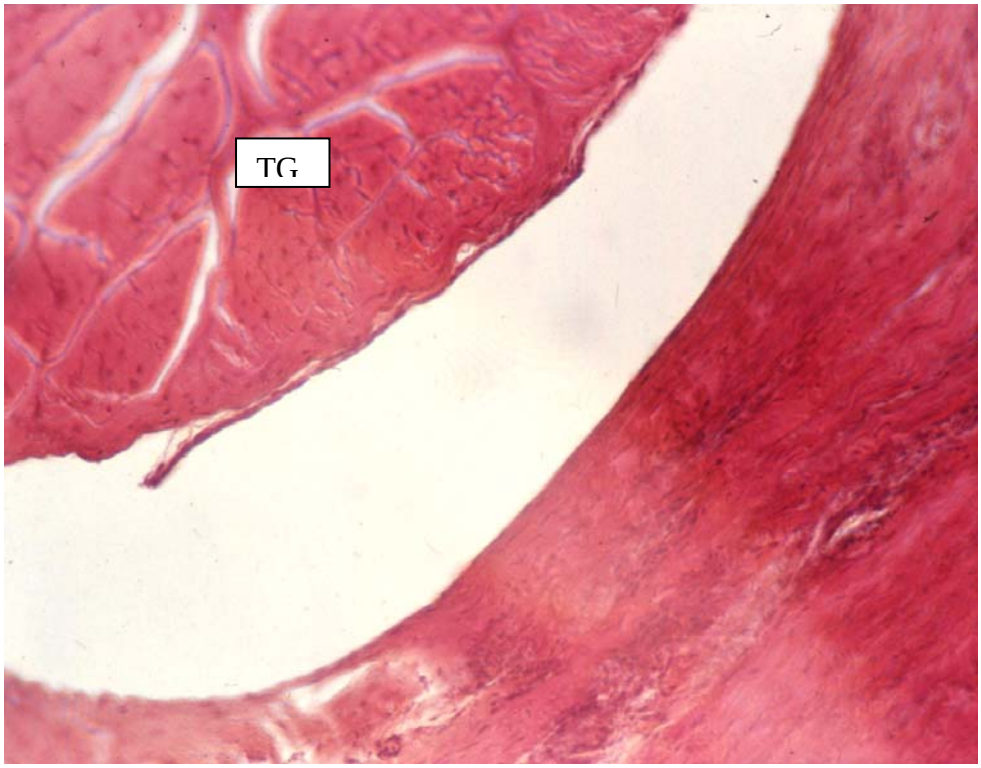


Fig.22 Newly formed chicken pseudo sheath TG: tendon graft.
Haematoxylin-eosin stain *(x25)*

2.4.3.2.Scanning electron microscopy:

On the surface of the newly formed visceral sheath, flat lining cells are covered with fine fibers and vehicles. The structure of the parietal sheath is uneven. The synovial cells and fibril network is similar to the parietal sheath. Fig.23,24,25.

Fig. 23 Scanning electron micrograph demonstrates flat lining cells (a*rrows)*

fibrils and vesicles on the visceral pseudosynovium *(x3000)*.

Fig.24 Surface folds and vesicles on the newly formed parietal tenosynovium *(x30)*

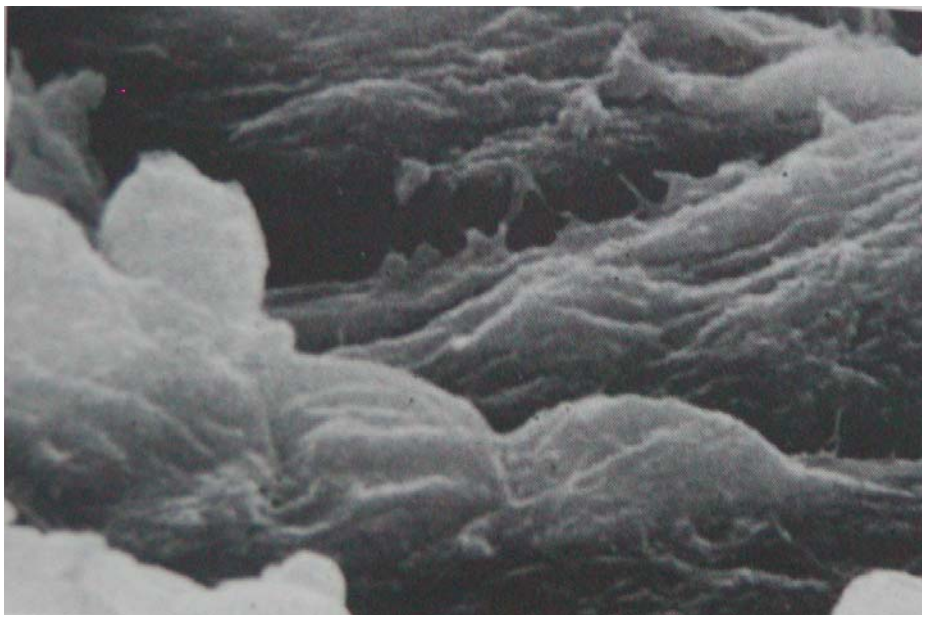


Fig. 25 Parietal pseudosynovium. Protrusions of lining cells covered with fibrillar network *(x3000).*

3.5.Discussion

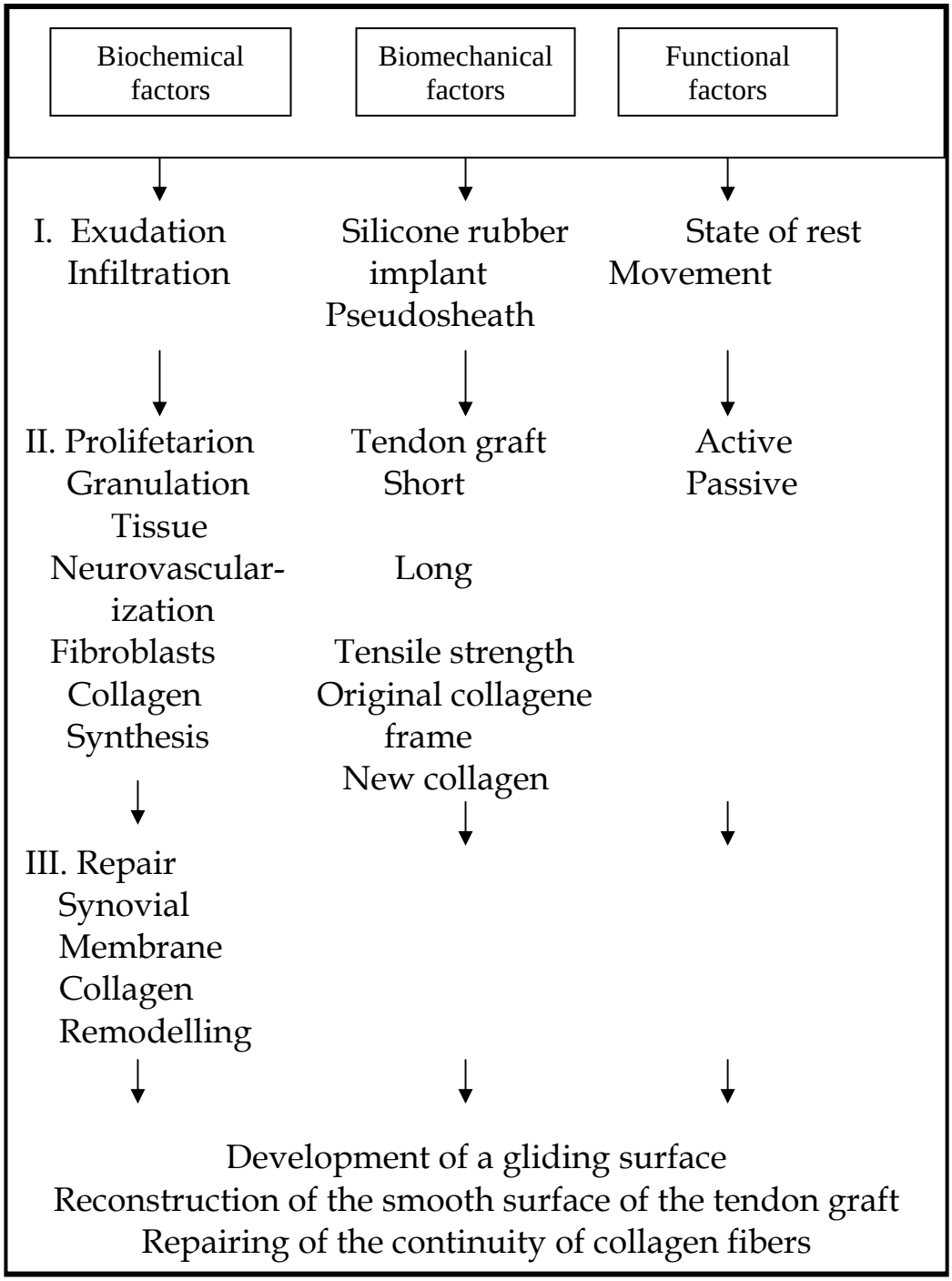
The structure of the synovial layer is controversial in the literature. Some authors did not find a continuous cellular lining of the normal synovial sheath or of the pseudosheath observing only an irregular tenosynovial layer (22, 23, 64, 7). Others have observed a regular tenosynovial surface, using scanning and transmission electron microscopy (21, 73,57, 85, 15). According to the scanning microscopic observations of the cellular protrusions of the lining cells of the vincula and the parietal sheath are covered with fibrils and vesicular particles, the synovial cells of the visceral surface are flat, enmeshed with filamentous fibrils. The structure described above has a similar built-up in both the normal and the pseudo

sheath. The same regular architecture was found both in the chicken and human sheath.

The ultra structure and function of the synovial cells were studied first in the joint synovial membrane. Two types of synovial cells have been recognized by transmission electron microscopy. Type A cells have phagocytic capacity with features of absorptive macrophagic cells. Type B cells have the ultrastructural characteristics of secretory cells producing probably protein and hyaluronic acid (33,15,78,74). According to Yehia and Duncan (85) and Eiken et al. (22), plasma dyalisate, containing protein, flows from the surrounding vascular tissue between the synovial cells to the joint space, to which is added mucin, secreted by the type B cells to lubricate and nourish the joint cartilage. The same situation can be found in the tendon sheath. Similar data have been found only by Schmidt and Mackay (57) concerning the tendon sheath. These authors described the type A and type B cells in the normal human tenosynovium. We have also found two types of synovial cells, and we have described the ultrastructural characteristics both in normal and pseudo sheath in chicken and human cases. The regular ultrastructure of the synovial membrane guarantees the nutritional supply and provides a gliding surface after tendon transplantation, not only normal conditions, but under reconstructions as well. The fact that a very important area for future research is the synovial fluid formed in the tendon sheath was declared by Lundborg in 1978 (77). The components of the synovia could probably prevent adhesion formation around the tendon. The normal and the newly formed synovial membranes are well vascularized. The undistributed microcirculation and the adequate production of synovial fluid make the tendon and graft nutrition possible. Under such

circumstances, first of all, the epitenon cells are proliferate and migrate into the suture zone and into the deeper part of the tendon graft synthesizing new collagen,

Biologic factors



The results of our experiment proved that the reorganization of the tendon graft takes place under this way undergoing a gradual reorganization (26). There is a possibility for intrinsic repair for the tendon graft under ideal conditions during the two stage procedure, according to the data from the literature and our experiments. The synovial fluid has probably important components to lubricate the newly formed sheath preventing adhesion formation. The neurovascular supply and the remodeling of collagen and early function are other important factors as well.

In some cases it is difficult to achieve the ideal healing conditions in clinical practice. Further investigations are necessary for the better understanding of the biological healing process altogether with its adaptation to the clinical practice. These efforts can result in the improvement of the final outcome after tendon reconstruction.

3.6 Conclusions

1. The normal visceral and parietal flexor tendon sheath contains regular layers of synovial cells. At 6 weeks the pseudo sheath has a similar appearance to the normal sheath.
2. The morphology and probably the function of type A and B synovial cells are also similar in the newly formed sheath.
3. Under ideal conditions the nutritional supply of the tendon graft is very important for the proliferation of the epitenon cells during the repairing process. According to our observation, the tendon graft undergoes gradual reorganization.

4.

Problems of the two-phase flexor tendon reconstruction.

IV. Clinical experiences

4.1Aims

The authors present their experiences with the two-stage tendon transplantation of Hunter. Their modifications and new results are given in detail. The indications of the method are also discussed by taking into account the preoperative evaluations. New methods are suggested for the treatment of injuries with bad prognoses. They also discuss possible future trends for research.

4.2 Introduction

The injuries of the flexor tendons are rather common. Initial treatment is essential in such cases, and they can determine the fate of the patient. In this regard it is especially sad that it is often impossible to give primer or delayed primary treatment due to the different reasons, such as the severe ness of the particular injury, other injuries, the danger of infections, or other reasons. These problems appear often in the injuries of the Verdan II zone, which belong to the worse group of injuries concerning prognoses (4). The most frequent reason of the bad functional

results are the “scat formation around the tendon” and the damage of the gliding surface (4, 6, 8, 14, 36, 56, 70).The decrease of movement is accompanied as a secondary effect with the joint contractures distally, while it causes the atrophy of the muscles proximally (9). There have innumerable attempts to make the results better in the “no man’s land”. One of these attempts is the usual tendon transplantation in one step, which makes it possible for the surgeon to perform the tendon suture outside the tendon sheath (56). Unfortunately, there are many cases, when the tendon injury is such that the conventional tendon transplantation is not sufficient or not promising at all. The literature shows the following methods used to try to prevent the scar formation around the tendon: 1., The use of artificial tendons 2., the use of blocking materials, that prevent scar formation between the tendon and its surrounding; 3., Use of pharmaceuticals to decreases the scar formation around the tendon 4., Development of a pseodosheath which provides a gliding surface to the transplanted tendon (8, 14, 27, 32).

It is this latter method that has been accepted most in the fight to decrease the scar formation around the tendon transplant since the beginning of the 1970s. Hunter and co-workers made good progress with the use of the Dacron reinforced silicone rod to produce a pseudosheath.Others also confirmed their results (36, 34, 32, 47, and 86).

We ourselves have been using this method based on our results with animal experiments (4, 6).

We have been trying to provide ideal conditions for the tendon transplantation to ensure the best results in out experiments. Cutely we have emphasized the important role of synovia in our recent experiments (71). We believe that – although is difficult to ensure indent conditions in

the clinical, to the lack or presence of many factors – our main goal is to get as close as possible to the ideal conditions (70, 71).

4.3. Material and method

4.3.1. Patient material

93 patients well treated between January 1. 1980 and December 31. 1990 using two-phase tendon reconstruction at the Dept. of Traumatology University Medical School Pécs and the Dept. of Traumatology Markusovszky County Hospital.

The follow up examinations were done in March 1992, at which 53 patients showed up. The evaluation was done by the same physician in all of the cases. The mean follow-up time was 3.2 years (between 0.5 and 7 years).

Those patients who had replantation or revascularisation were excluded from the follow up. There were 44 men and 9 women. In 27 cases the right, while in 26 cases the left hand was involved. The types of fingers involved and the causes of the injuries are shown in Figs. 26 and 27, respectively.

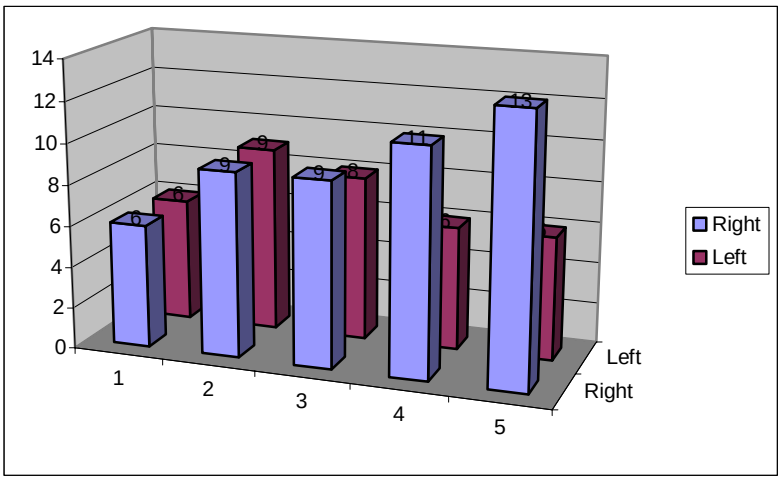


Fig26.

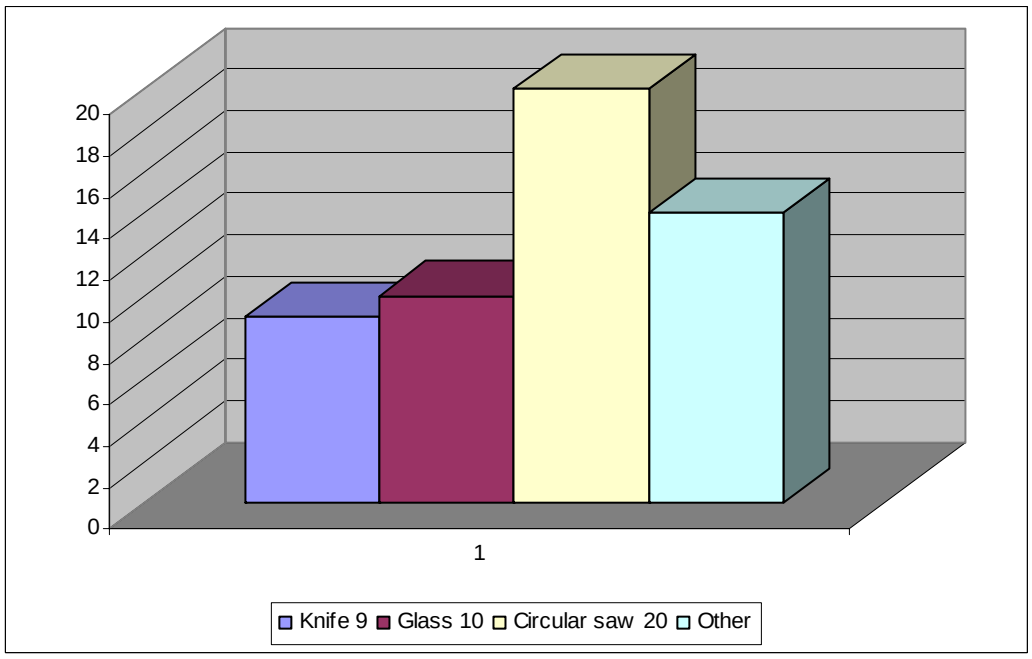


Fig 27.

4.3.2 Type of injury

Serious injuries caused by lawn mowers or by plane machine appear under the "other" injuries. Indications for the two-step tendon reconstruction were:

- Conquassating injury
- Previous unsuccessful surgery
- Extending scar formation of the tendon sheath
- Previous infection

4.3.3. Preoperativ grouping

According to the preoperative grouping all operated patients belonged to either the acceptable or the bad prognosis category. Before the surgeries intensive physiotherapies were applied to ensure the largest possible movement-range. This physiotherapy had a good effect on the stub of the soft tissues as well.
The time between the injuries and the first phase of the tendon reconstruction was, on average, 2-7 months (between 1 and 6 months).

4.3.4. Surgical technique

In most cases zigzag incisions were applied, recently we prefer to use middle-lateral incision based on biomechanical considerations (12). We are careful not to damage the intact parts of the tendon sheath. We take

out all scary tissues while trying to carefully preserve the A2 and A4 pulleys. In case of extensive scaring the pulleys are replaced.

We have been using simple silicon rods with 4 or 5 mm diameters, since we do not have original silicon rods reinforced by Dacron. The silicon rod is securely fixed beneath the distal stump of the FDP. The proximal end of the silicone rod is placed beneath the proximal stump of the flexor tendon, but without any fixation. If only the fingers have scar formation we use short silicon rods, while in case of having extensive scarring on the palm as well, we use long ones, which reach the carpal region. After the first phase the hand is immobilized in functional position for 3 weeks. After the removal of the cast another intensive physiotherapy follows, trying to achieve as good passive movement as possible.

The time elapsed between the first and second phase was generally between 3 and 4 months, with the shortest time period of 6 weeks.

In the second operative phase the injured finger is opened only proximally and distally from small cut. We locate the ends of the silicon rod and with the help of the rods we pull a thick thread into the new pseudo-sheath, and with that we pull the transplant into place. In most cases the tendon of m.palmaris longus was used as transplant. In a few cases the plantaris tendon or extensor tendons taken from the dorsum of the foot were used (Fig.28.).

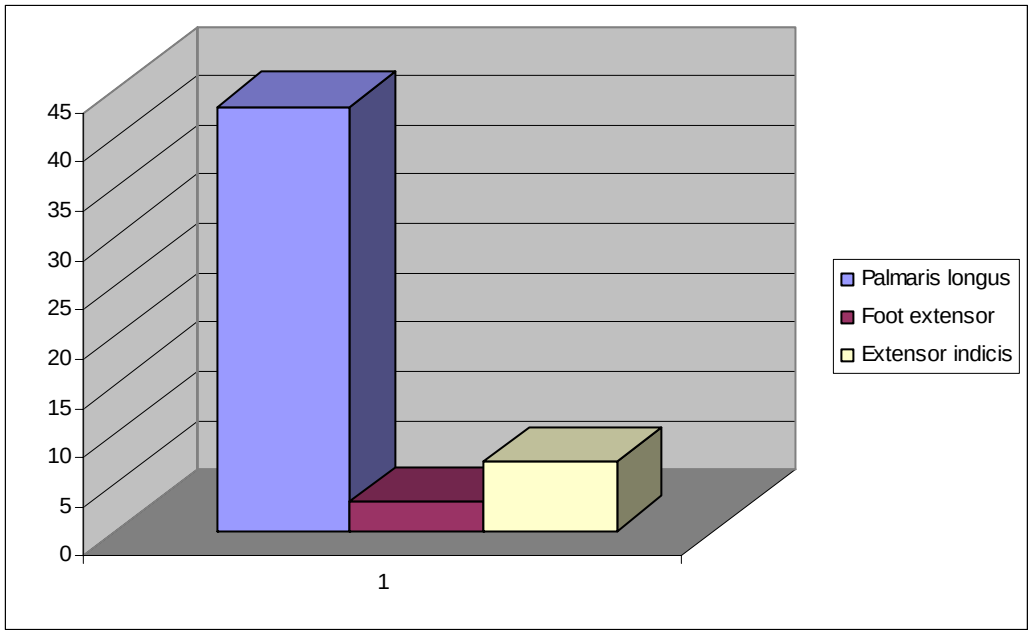


Fig.28.

The tendon transplant was fixed with the Pulvertaft method proximally and the Bunnel method distally. The exact set up of the tension of the transplant has a paramount of importance. The hand is immobilized with Kleinert cast after the surgery. The early, controlled mobilizations are started on the 3-5 days after the surgery. The immobilization time is 3-4 weeks, followed by active physiotherapy with professional physiotherapists.

4.4. Results

The follow up examinations of the of the patients was done using the Buck-Gramcko scheme. The results were excellent for 8, good for 20, acceptable for 14, and bad for 15 fingers, respectively. Our results are slightly worse than the ones given in the literature, due to the more than average bad results. At the same time about half of our patients belonged to the bad preoperative prognosticated group, and that is higher than in

the literature data. The complications and the treatments there off are shown in Fig.29.

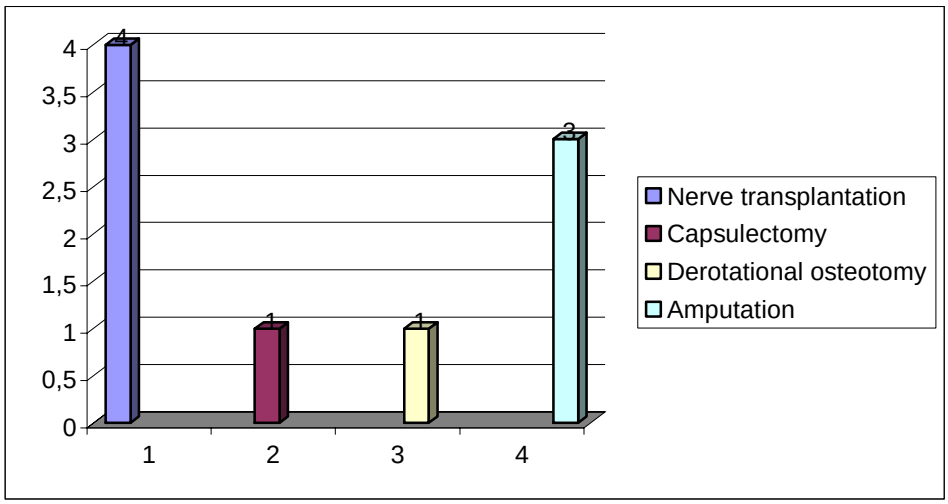


Fig.29.

4.5. Case presentation

B.Gy. 47 old man. His left ring-finger was damaged by a circular saw . His first treatment was done elsewhere. He was accepted in our clinic for the purpose of a reconstruction surgery after 3 months. We performed a silicon rod implantation, followed later by a palmaris longus transplantation. The results, 2 years after the surgery, is excellent (see Figs.30ABC).

Fig. 30.A.

Fig. 30. B.

Fig.30.C.

4.6. Conclusion

Our experience shows that the two-phase tendon reconstruction described by Hunter [36, 34, 32, 47, 86] is a successful method in the treatment of injuries having both acceptable and bad preoperative prognoses. Using the right surgical techniques, the method is both safe and relatively simple. At the same time, we also have to say, that with patients of bad preoperative prognoses we experienced several times contractures appearing gradually in the postoperative stage. It is not clear what caused this, perhaps the gradual scarring of the new pseudo sheath. We worked out several methods to rule out this problem; we replace only the scary part in case of moderate scar formation (4, 6), meanwhile in case of extensive scarring the whole tendon-tendon sheath unit is replaced. Several other promising methods use also being tested.

The results with the active artificial tendon transplant are also very promising (36, 34, and 32). This method also ensures keeping the function of the muscles.

Our conclusion is that the two-phase tendon transplantation is a promising and good, albeit not the only possible, method for most injuries involving flexor tendon injuries with bad prognoses. Those results that were achieved with animal experiments needs ideal conditions, usually cannot be reproduced in human injuries due to different biological and clinical factors. It is the experienced hand-surgeon, who can determine based on the preoperative examinations what the best surgical procedure should be.

Only this way can we expect good results with such tendon injuries that have bad clinical prognosis. We hope that there will be further improvements in this field based on new experiments and new clinical data.

5.

New results

The results of the experimental investigations of flexor tendon reconstruction and the clinical experiences can be summarised as follows:

5.1. Investigations of the experimental model:

1. That new fact has a paramount importance, the chicken third (long) toe has a devided tenosynovial sheath. We have to take into account during the experimetal planning this fact, the FDP (flexor digitorum

profundus) is running in a separate tendon sheath from the insertion of the vinculum longum.

2. The exact description of the pulleys of the third (long) toe of the chicken, and introduction of a new terminology.

3. The description of the vincular system of the third (long) toe of the chicken feet. It was established the FDSD (flexor digitorum superficialis distalis) has a separate vincula.

4. The exact circulation of the third (long) toe of the chicken was described, and the presence of the digitopalmar arch was verified as well.
5. It was pointed out, the light-, and electron microscopical structure of the third (long) toe of the chicken toe has a very similar structure to the human tendon-tendon sheath unit.

5.2. Comparison of the ultra structure of the normal tenosynovium and the pseudo sheath.

1. Type A (phagocytic capacity) and type B (secretory capacity) synovial cells were demonstrated in the chicken as an experimental model, in the pseudo sheath in chicken and in the human tenosynovium.

2. It was proved experimentally, the incorporation of the tendon transplant built in with an intrinsic mechanism.

3. The role and importance of the synovia was emphasized during the tendon healing.

5.3. Clinical experiences during two phase tendon reconstruction.

1. Ideal circumstances were provided according to the experimental data during the clinical practice.

2. The choose the most appropriate surgical method according to the preoperative prognosis.

3. The results were evaluated compared to the preoperative prognosis.

5.4. Summary of the results, further plans for the future.

The chicken third (long) toe tendon-tendon sheath unit was used as an experimental model. We were able to establish, nowadays this model is the most convenient for the experimental investigations in flexor tendon research. The planning of the experiments can be more accurate with our exact description of the differences; the comparison of the clinical data could be much more realistic. Our ultra structural investigations pointed out the extraordinary similarity between the

structure of the chicken and human tendon-tendon sheath unit. It was also established the pseudo sheath after silicon rod implantation has a very similar ultra structure both under experimental circumstances and in the clinical practice. This similarity emphasize the role of the synovia in the healing of the tendon wound and in the incorporation of the tendon graft

The clinical results correlate very well to the experimental results and data. The similar approach of "the ideal state" in the clinical practice, used during experimental circumstances, improves the results.

We emphasize the importance of the synovia according to our experimental data.. Therefore the examination of the synovia has a paramount importance. It can help to understand the normal, physiological processes. On the other hand it can provide further possibilities to decrease the adhesion formation around the healing tendon. If the exact content of the synovia is known we will have the possibility to influence the content using drugs. With this chemotherapy we would improve the circumstances of the tendon healing without further surgical intervention.

An other possibility could be in the improvement of late results the use of new techniques in the tendon sheath closure and replacement using the given experimental data.

6.

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7.

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